PROGRAMMING IRRIGATION FOR GREATER EFFICIENCY

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Introduction

Programming irrigation for greater efficiency implies maximizing water use efficiency. However, though this in itself is an important objective for water deficient areas, the farm manager or owner is more interested in maximizing his net income by optimum use of irrigation water, fertilizers, and other inter-related inputs. Fortunately, if maximum net income is achieved, optimum water use efficiency usually has also been attained. More progress toward greater efficiency can be expected by working toward the goal of greater net income rather than greater water use efficiency, per se.

Evaluations of farm irrigation practices in the western United States during the late 1950's and early 1960's (Tyler et al., 1964; Willardson, 1967) showed little change in irrigation scheduling practices in 25 years (Israelsen, 1944). No single factor related to the system, soil, or crop appeared to be limiting irrigation efficiency. During this same era, irrigation science and technology made significant advancements.

There are two major reasons why irrigation scheduling practices, involving both timing and amount of water applied, have not changed substantially: (1) The needs of managers of irrigated farms and the acceptability of suggested scheduling procedures have not been adequately evaluated; (2) The cost of irrigation water often has not been significant, and indirect costs such as yield reductions caused by delayed irrigations and additional nitrogen requirements created by excessive water applications are not easily recognized or quantified. Also, crop and soil damage costs encountered on lower-lying areas by excessive water use on upper areas are not always borne by the upper-

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area irrigators.

Irrigation scientists and technologists know how to optimize production by manipulating irrigation practices, but these specialists are not making current irrigation decisions on each farm. Irrigation decisions are made by people who have limited time and training. They do not have the meteorological and crop growth data and forecasts to predict the next date of irrigation so that farm work can be planned accordingly. The modern farm manager can acquire irrigation equipment to apply the amount of water needed when it is needed, but he still must decide "when" and "how much" water to apply. Predictions of needed irrigation several days in advance are essential for planning other farm work and for completing the required irrigations when the capacity of the irrigation system or allotted flow is limited.

Basically, current estimates and predictions of irrigation needs are not available to most managers of irrigated farms, or at least they are not available in a form that can be used. Irrigation scheduling is a decision-making process requiring current information, trends, projections, and alternatives much the same as required by managers of large industries. The modern farm manager needs and wants a continuing service that gives the present soil water status on each of his fields, predicts irrigation dates, and specifies the amounts of water to apply on each field. He could also use predictions of adverse effects, such as the effects of delaying an irrigation for several days, or perhaps terminating irrigations, on the yield of marketable products. This information would increase the manager's skills in making better and more profitable irrigation decisions.

An irrigation management service is often needed to supplement practical irrigation experience with irrigation science on a day-to-day basis. The potential economic returns to the farm manager or owner can exceed the cost of this service severalfold. Moreover, the increase in net income to the farmer and greater water use efficiencies are not the only benefits to be derived from this service. The recipients of the irrigation forecasts have found the data to be useful in planning other farm work, such as cultivation and spraying for insect control. In semihumid areas, it might enable farmers to begin irrigating their crops in sufficient time to cover all of the fields before soil

moisture deficits become severe. With the current high in-
terest and enthusiasm by the managers of irrigated farms in
the United States for a service such as this, and the es-
tablishment of new irrigation service companies or the ad-
dition of irrigation scheduling services to existing compa-
nies, it is expected that a significant portion of the ir-
rigated farms in the United States will be scheduled using
procedures such as described in this chapter within the
next few years.

Alternative Methods of Improving Irrigation Programming

There are currently four general approaches to improv-
ing irrigation scheduling practices.

A. Irrigation Programming Instruments

Tools and instruments, such as tensiometers, soil water
blocks, evaporation pans, and soil sampling augers and
tubes have long been recommended or supplied to farm mana-
gers with instructions for their use. These instruments
are often supplemented with guides to interpreting the re-
sults obtained. This has been the general approach taken
by most irrigation technologists during the last three dec-
ades to improve irrigation water management, and there are
numerous technical publications and manuals on this subject.
New and better soil water instruments are technical aids to
the solution of the problem, but do not in themselves en-
sure a practical solution, as evidenced by continued poor
irrigation practices in many areas.

B. Irrigation Management Services Using Instruments

An irrigation management service by trained service
groups or private firms using some of the tools mentioned
in the previous section is a practical alternative and is
being used to a limited extent in some areas of the western
United States. Average evapotranspiration data determined
experimentally in the area may be used for predicting the
date of the next irrigation. Irrigation management servi-
ces based on soil sampling are in use in Arizona and Wash-
ington, U.S.A. (Franzoy and Tankersley, 1970; Marshall,
1971). In general, a service involving soil sampling has
not been widely adopted because farm managers are not

always aware of the need and benefit of good irrigation water management. Services using tensiometers are more common, especially with high-value crops, but these instruments must be read frequently, which involves significant travel and labor costs.

C. General Irrigation Forecasts

Generalized forecasts of irrigation needs for common crops and the major soils in the area based on local or regional experimental data are frequently used in areas needing only infrequent supplemental irrigations. This approach is economical, but generally requires the farm manager to interpret the forecasts and monitor his own fields to verify the predictions (Jensen, 1969). This type of service has also been adapted to arid conditions. For example, a general forecast service is being developed in southern Idaho with the predictions provided by the U.S. Bureau of Reclamation and the A & B Irrigation District of the Minidoka Project (Brown and Buchheim, 1971).

D. Field Scheduling and Monitoring

Irrigations are predicted for each field utilizing meteorological data combined with soils, crop, and experimental data, but these predictions are supplemented with a field monitoring service. This alternative has been tried and is readily accepted by the managers of irrigated farms (Jensen et al., 1970; Franzoy and Tankersley, 1970).

Irrigation Management Service Requirements

The scientific knowledge to estimate and predict the depletion of soil water by evapotranspiration has been the subject of world-wide research since the late 1940's, but estimating or predicting soil water depletion solves only part of the problem. Some of the additional requirements that are essential in providing an irrigation management service are described in this section.

A. Technical Competence

A service group such as a governmental agency, irrigation district, or a private firm must have the necessary

technical competence to collect and interpret essential basic data and develop the predictions. There are advantages in private groups providing this service, as the private consultant can supply other personalized management services to the farm manager. Many private firms, for example, have the skills in other areas such as fertilizer management, pesticide control, cost accounting, and general agronomy. Private service groups should develop self-regulating standards of staff competence to assure dependable recommendations for irrigation clients. If this is not done, state licensing as required for other professional services, will soon be required.

B. Economic Feasibility

Unwarranted accuracy or complexity should be avoided in order for a service to be self-supporting. The costs of an irrigation scheduling service should be economical relative to other irrigation operation and maintenance costs. This means that expensive instrumentation and detailed measurements on each farm probably will not be feasible. Also, it means that some basic meteorological data cannot be used because complicated instrumentation, data processing, and instrument servicing would be required. The service company or agency must utilize meteorological data that are easily obtainable from existing weather stations, or that can be obtained with reliable instruments that function throughout the season with few or minor mechanical problems.

C. Basic Farm Data and Records

The servicing group must collect background information on each field, including soils data, the crops to be grown, past cropping history where soil fertility is involved, characteristics of each existing irrigation system, and current practices of each farm manager. It must also maintain essential records for each farm and field involved. If a generalized service is provided, the amount of record keeping involved is substantially reduced, but the accuracy of generalized forecasts for each field may be lower, especially if field monitoring by skilled technicians is not provided.

D. Communications

When operating on a field-by-field basis, a two-way communication system must be an important part of the program and has been one of the major problems encountered by service groups. Complete reliance on a mail service has not been fully satisfactory because of the time lag occasionally encountered. Also, farm managers frequently neglect to promptly provide the desired feedback information, such as the date a field has been irrigated, which would be valuable even to a company that relies on soil sampling. A telephone service for collecting the feedback information has been tried. However, this procedure has not been satisfactory because the farm manager frequently is not in when called, or the service company office may be closed when the farm manager chooses to make his own call. Private service groups in Southern Idaho are considering installing automatic telephone recording systems so that the farm manager can call the service center and provide feedback information at his convenience.

The Salt River Project at Phoenix, Arizona, is contemplating using remote computer terminals connected by telephone network to a central computer. The remote terminals will be located in outlying field offices where the farm managers regularly stop to order irrigation water. The terminal operator can reach the central computer files and obtain an updated printout for the manager's farm without delay. The printout lists the predicted irrigation dates for each of the fields involved in the scheduling program. This arrangement is desirable when an irrigation district is providing the service since it also controls water distribution and maintains records of irrigation water deliveries. As an alternative, the Salt River Project is evaluating the use of a time-sharing terminal in the main office with data available to the field by telephone.

E. Verification and Field Inspection

The success of an irrigation management service will, to a large extent, depend on periodic monitoring or soil samplings of the fields to verify the adequacy of previous irrigations and the accuracy of predicted irrigation dates. This part of the service can be provided by a technician experienced in irrigation water management, or the soil

sampler in a soil sampling program. Preferably, one tech-
nician serves a specific group of farm managers so that the
manager develops a personal rapport with his service tech-
nician. He looks to the technician or his supervisor as an
expert in irrigation water management, and one who can also
provide guidance on other aspects of surface or sprinkler
irrigation. The Salt River Project at Phoenix, Arizona
utilizes technicians in this manner with one technician
serving about 20 farms. He visits each farm weekly, and if
he encounters questions that he cannot answer, his vehicle
is equipped with a two-way radio so that he can call his
supervisor or a specialist in the central office to obtain
a specific recommendation.

Meteorological Data Limitations

Energy balance and, in some cases, mass transfer meas-
urements have become reliable and accurate methods of de-
termining daily evapotranspiration in experimental studies.
However, the cost, technical skills, and data processing
required effectively prohibit these techniques on a contin-
uing daily basis even for a single reference field within a
project. Instead, estimates of "potential evapotranspira-
tion," or evapotranspiration that occurs with a well-wa-
tered reference crop like alfalfa with 30 to 50 cm of
growth within the area, are adequate. Also, if a combina-
tion equation is used, only daily values of meteorological
data are needed to provide the necessary accuracy of ± 10
to 15% on a daily basis. The accuracy for 5- to 20-day
periods will be better if the errors are random.
There are also other problems in obtaining the neces-
sary meteorological data. In some areas, a service company
must establish its own weather station. In the Western
United States, a weather station centrally located within
an irrigated project of 50,000 to 100,000 hectares can pro-
vide adequate data to compute the daily evaporative demand.
Observer skill and instrument calibration are major prob-
lems encountered in the collection of meteorological data.
Table 1 indicates the degree of skills that should be con-
sidered when collecting various meteorological data. This
table is based on personal experiences of encountering er-
roneous data where meteorological stations are not properly
maintained, or where meteorological readings are not taken
by trained technicians. Some of the refined measurements

required for energy balance computations may actually require a scientist's daily attention. Since this degree of skill is not practical for most irrigation scheduling services, procedures that require daily, precise meteorological measurements are restricted.

TABLE 1

Technical Skills Required to Obtain Reliable Daily
Meteorological Data on a Routine Basis without Daily
Supervision by a Research Engineer or Scientist.
(The x's denote an acceptable level of training.)

Meteorological parameters	Training required		
	Observers	Technicians	Meteorologists
Air temperatures			
Max-min thermometers	x	x	x
Thermographs	x*	x	x
Humidity (dew point)			
Sling psychrometer	x*	x	x
Hygrograph	-	x*	x
Wind (daily run)			
Integrating anemometer	x*	x	x
Solar radiation (daily)			
Actinograph	-	x†	x*
Integrating unit (sensor-integrator)	-	x†	x*
Sunshine hours	-	x*	x
Net radiation			
Integrating unit	-	-	x*
Evaporation			
Standard pans	-	x*	x

* Periodic calibration, maintenance and instruction needed.
† Periodic calibration, maintenance and instruction by a trained meteorologist, research engineer or scientist.

Effective Use of Regional Experimental Data

In the U.S.A., the amount of research data available
for most large irrigated areas is often extensive and rep-
resents a large investment of private and public funds.
The interpretation of experimental data for optimum irriga-
tion water management requires skills in the science of
agronomy and plant-soil-water relations. Similarly, the
collection and interpretation of soils data available from
previous experiments requires practical knowledge of soil-
water principles. Workshops are frequently conducted for
farm managers. Similar but more technical workshops are
needed for the professional staff members of service compa-
nies. There are some circumstances in which knowledge of
soil-water storage is of no avail. These usually occur
when the irrigation system can apply only a limited amount
of water per irrigation, less than the generally allowable
soil water depletion for a given soil and crop, and when
expected rainfall is insignificant. In such cases, the ac-
tual allowable depletion of soil water between irrigations
will be largely determined by the irrigation system and not
by soil characteristics.

USDA-ARS-SWC Irrigation-Scheduling Computer Program

A. History of Development

The USDA computer program was developed cooperatively
with farm managers and service groups as a tool for provid-
ing managers of irrigated farms with scientific estimates
of irrigation needs for each field. This approach is not
the only solution to the problem, but it is one that has
gained rapid acceptance. The computer program requires
limited input data and uses simple, basic equations so that
each can be replaced as more accurate relationships are de-
veloped. The principles and procedures involved are de-
scribed in several recent publications (Heermann and Jensen,
1970; Jensen, 1969; Jensen and Heerman, 1970; Jensen et al.,
1971). A summary of the computer program is given in the
next section.

The basic components of the irrigation management ser-
vice were evaluated in 1966 and 1967 in southern Idaho.
The computer program was evaluated in 1968 and 1969 on
about 50 fields in Idaho and a similar number in Arizona by

the Salt River project (Franzoy and Tankersley, 1970).
During 1970, a number of service groups and companies
gained experience in the use of this general concept of ir-
rigation scheduling. The Salt River Project at Phoenix,
Arizona, for example, has used the program for three years.
After the first two years, the original program was revised,
retaining the basic components, but the input-output data
and format and some of the crop curves were changed to fit
local facilities and crops (Franzoy and Tankersley, 1970).
The irrigation predictions should be updated twice a week
when shallow-rooted crops are involved or when evapotrans-
piration rates are high. Weekly updating suffices for most
field crops.

The U.S. Bureau of Reclamation has modified the program
to provide general irrigation forecasts for major crops in
an area. This service was made available to southern Idaho
for 54 farm operators in 1970. A field-by-field scheduling
and monitoring service was provided for 68 fields on 15
farms within the same area (Brown and Buchheim, 1971). The
general forecasts were updated once a week and distributed
to cooperators who provided their own field monitoring. An
agricultural technician made weekly visits throughout the
irrigation season on the 15 farms on the field-by-field
program. Additional changes have been made for 1971 which
include both the General Irrigation Forecasts and Field
Scheduling and Monitoring Methods. These methods will be
used in 1971 on two irrigation districts in southern Idaho
with field monitoring provided by trained technicians on
each farm.

An agriculture technology company in McCook, Nebraska
is using a modified version of an earlier program in Ne-
braska and Kansas (Corey, 1970). This company is also
planning to add fertilizer management to its service in
1971.

Approximately 8,000 hectares were scheduled in 1970 by
various groups in Idaho, Nebraska, and Arizona. An esti-
mated 50,000 hectares will be scheduled in 1971, with near-
ly half of the area involving cotton on the Salt River Pro-
ject. Other private companies are adding this service to
their regular farm management services in Idaho, Washington,
Kansas, and California. The Bureau of Reclamation is also
expanding its irrigation management program to other areas
such as the Central Valley of California, and the Rio
Grande Valley of Texas.

The concept of scheduling irrigations using climatic data is not new. Das (1936) suggested using climatic data to control irrigations in the 1930's. The concept received more attention following the publications of Penman (1948, 1952) and Thornthwaite (1948). In 1954, Baver stated:

> The meteorological approach to irrigation has the advantage of simplicity of operation when compared with methods based upon measurement of soil moisture changes. If it is proved satisfactory, the costs of using this system would be relatively small. Undoubtedly, new techniques will be developed that will give an integrated measure of daily temperature, sunshine and solar energy. When such methods are available, meteorological data can be correlated better with evapotranspiration.

Many others have since discussed this approach (Baier, 1957, 1969; Pierce, 1958, 1960; Pruitt and Jensen, 1955; Rickard, 1957; van Bavel, 1960; van Bavel and Wilson, 1952). However, prior to 1965 this method had not been adapted for general practical use or tested extensively in the United States. The Penman equation is often referred to as being too complex for practical use (Fitzpatrick and Cossens, 1965). However, with modern low cost computers, there is no justification in using less refined methods of computation when the meteorological data are easily obtainable.

B. Operating Costs

The current costs of this service range from $4.00 to $10.00 (U.S.) per hectare. The lower cost is for large acreages, crops requiring less frequent monitoring, and short-season crops.

C. Operational Steps

The program first estimates daily evaporative flux from a well-watered reference crop like alfalfa with 30 to 50 cm of top growth, E*. The basic meteorological data required for this estimate are: (1) daily maximum and minimum air temperatures; (2) daily solar radiation; (3) average daily dewpoint temperature or dewpoint temperature observed at or near 8:00 A.M.; and (4) daily wind run at a known height,

preferably in an open area over a surface that does not change significantly in roughness or displacement height during the growing season. Prior to 1971 (Jensen et al., 1971), the combination equation as presented by Penman (1963) was used in the following format:

$$E^* = \frac{\Delta}{\Delta + \gamma} (R_n + G) + \frac{\gamma}{\Delta + \gamma} (15.36)(1.0 + 0.0062u_2)(e_s - e_d) \tag{1}$$

where Δ is the slope of the saturation vapor pressure-temperature curve, (de/dT), mb $°C^{-1}$; γ is the psychrometric constant (0.66 mb $°C^{-1}$ at $20°C$ and 1 bar pressure); e_s is the mean saturation vapor pressure in mb (mean at maximum and minimum daily air temperatures); and e_d is the saturation vapor pressure at mean dewpoint temperature in mb; u_2 is total daily wind run in km day^{-1} at a height of 2 m; R_n is net radiation in cal cm^{-2} day^{-1}, and G is heat flux from the soil in cal cm^{-2} day^{-1} (negative when the heat flux is to the soil). The parameters $\Delta/(\Delta + \gamma)$ and $\gamma/(\Delta + \gamma)$ are mean air temperature weighting factors whose sum is 1.0.

Since the percent of sunshine or degree of cloud cover, normally used to estimate net longwave radiation, are generally not available, or are qualitative rather than quantitative, procedures were developed for estimating net radiation using observed daily solar radiation, R_s, relative to solar radiation that would normally be expected on that day if there were no clouds, R_{so}. Cloudless-day values can be obtained from various tables such as those by Fritz (1949) or Budyko (1956) or by plotting observed solar radiation to obtain an envelope curve through the high points. Net radiation in cal cm^{-2} day^{-1} is then estimated as follows:

$$R_n = (1 - \alpha) R_s - R_b \tag{2}$$

where α is the mean daily shortwave reflectance or albedo, and R_b is the net outgoing longwave radiation. An albedo of 0.23 is currently used in the program. R_b is estimated as follows:

$$R_b = (a_1 \frac{R_s}{R_{so}} + b_1) R_{bo} \tag{3}$$

where R_{bo} is the net outgoing longwave radiation on cloudless days. The constants a_1 and b_1 derived with data from

Davis, California[1] are 1.35 and –0.35, respectively, and
for Idaho 1.22 and -0.18, respectively (Wright and Jensen,
1971).

The net outgoing longwave radiation on cloudless days
is estimated using:

$$R_{bo} = (a_2 + b_2 \sqrt{e_d})(11.71 \times 10^{-8}) \frac{T_2^4 + T_1^4}{2} \qquad (4)$$

where e_d is the saturation vapor pressure at mean dewpoint
temperature in mb; 11.71×10^{-8} is the Stefan-Boltzmann
constant in cal cm^{-2} day^{-1} $°K^{-4}$; and T_2 and T_1 are the max-
imum and minimum daily air temperatures, respectively, in
$°K$. The constant, a_2, formerly used was 0.32. However,
recently a slight variation in the constant a_2 improved the
estimates of net radiation (Wright and Jensen, 1971):

$$a_2 = 0.325 + 0.045 \sin [30(M + D/30 - 1.5)] \qquad (5)$$

where M is the month, 1-12, and D is the day, 1-31. The
constant, b_2, now used is-0.044, which is the average of
the value obtained by Goss and Brooks (1956) in California,
0.040, and the value obtained by Fitzpatrick and Stearn
(1965) in Australia, 0.049. These constants in the Brunt
equation for effective atmospheric emittance were found to
be more suitable for arid conditions than those originally
proposed by Penman.

Daily soil heat flux, G, is estimated with a simple em-
pirical equation using the difference between mean daily
air temperature and the average temperature for the three
previous days. This component is currently being revised.
For practical purposes, it can be assumed to be zero under
a crop with a full cover, such as alfalfa.

Estimates of daily evaporative flux for the reference
crop, E*, in cal cm^{-2} day^{-1}, are converted to depth equiva-
lent, E_{tp}, using 585 cal g^{-1} as the heat of vaporization.
Evapotranspiration for a given agricultural crop, E_t, is
estimated from the daily reference evaporative flux as fol-
lows:

$$E_t = K_c E_{tp} \qquad (6)$$

where K_c is a dimensionless coefficient similar to that

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[1]W.O. Pruitt, personal communication.

proposed by van Wijk and De Vries (1954) and Makkink and van Hermst (1956). This crop coefficient represents the combined relative effects of the resistance of water movement from the soil to the various evaporating surfaces and the resistance to the diffusion of water vapor from the surfaces to the atmosphere, as well as the relative amount of radiant energy available as compared to the reference crop (Jensen, 1968).

$$K_c = \frac{R_n + G + A}{R_{no} + G_o + A_o} \tag{7}$$

where A is the sensible heat flux to (-) or from the air (+) and G is the sensible heat flux to (-) or from the soil (+); and R_n is net radiation to the crop-soil surface (+). The subscript o designates concurrent values for the reference crop in the immediate vicinity (in this case, alfalfa). The major term affecting K_c is A, which is usually negative on a daily basis for crops with small amounts of leaf area in arid zones, but it may be positive for alfalfa. The crop coefficient can also be expressed in terms of mean daily Bowen ratios and net radiation (Jensen, 1968).

Typical examples of the effects of growth stage on the crop coefficient where soil water is not limiting have been presented for grain sorghum by Jensen (1968), and for corn by Denmead and Shaw (1959). More recently, there have been numerous publications presenting observed relative rates of evapotranspiration as compared to an estimate or measurement of the evaporative potential (e.g., Ritchie, 1971; Ritchie and Burnett, 1971). Mathematical models of K_c based on leaf area index, leaf stomatal resistance to diffusion of water vapor, soil water, and other relevant parameters, may be used in place of experimental values when they become practical for use with limited data.

Since the actual crop coefficient K_c is generally influenced by the wetness of the soil surface, it is automatically adjusted in the computer program as follows:

$$K_c = K_{co}K_a + K_s \tag{8}$$

where K_{co} is the expected crop coefficient based on experimental data where soil water is not limiting and normal plant densities are used; and K_a is the relative coefficient related to available soil water. Currently K_a is assumed to be proportional to the logarithm of the percentage

of remaining available soil moisture (AM):

$$K_a = \underline{\ln}\ (AM + 1)/\underline{\ln}\ 101$$

K_s is the increase in the coefficient as a result of the soil surface being wetted by irrigation or rainfall. The maximum·value of K_c normally will not exceed 1.0 for most crops. Currently, the values for K_s for the first, second and third day after a rain or irrigation have been taken as follows: $(0.9 - K_{co})\ 0.8$; $(0.9 - K_{co})\ 0.5$; and $(0.9 - K_{co})\ 0.3$, respectively.

Soil water depletion after an irrigation is calculated as follows:

$$D = \sum_{i=1}^{n} (E_t - R_e - I + W_d)_i \qquad (9)$$

where D is the depletion of soil water (after a thorough irrigation $D = 0$); R_e is effective rainfall (excluding runoff); I is irrigation water applied, W_d is drainage from the root zone or upward movement from a saturated zone; and $i = 1$ for the first day after a thorough irrigation when $D = 0$. The terms on the right hand side of the equation are daily totals in centimeters.

The date of the next irrigation is predicted by the remaining soil water that can be safely depleted and the current average E_t.

$$N = \frac{D_o - D}{\bar{E}_t} \qquad (10)$$

$$N = 0 \text{ for } D > D_o$$

where N is the estimated days to the next irrigation if no rain occurs; D_o is the current optimum depletion of soil water in cm; D is the estimated depletion to date in cm; and $\bar{E}_t$ is the current mean rate of E_t in cm day^{-1}. The magnitude of D_o will vary with each crop and field, and will be partially dependent on the irrigation practice used. The amount of water added to a given soil by furrow irrigation during a 12-hour irrigation, for example, will be affected by furrow slope, stream size, etc.

The amount of water required for the next irrigation, W_I, is calculated by dividing D_o by the attainable efficiency for the irrigation system.

Adjustments for leaching can be made, if necessary. At this time periodic monitoring of the salt concentration in the soil is recommended. If the amount of water applied and its salt concentration are known, then automatic adjustments for leaching can be added to the program.

D. Input Data

There are three categories of input data required which should be provided by the service groups working with the farm managers.

Basic Data: Basic data consist of the regional constants for the E* equations, taking into account the differences in height of wind measurements, and the crop-soil system data for each field. The latter item involves the farm name, crop code number, crop-field identification, planting date, estimated effective cover date, estimated harvest date, estimated overall irrigation efficiency for each field based on the system being used, and the maximum amount of soil water that could be depleted by evapotranspiration for each crop. The maximum depletion by evapotranspiration is estimated as the difference between a soil water content about four days after irrigation of a soil that is about 60 to 90 cm deep and has been covered to prevent evaporation (Miller, 1967), and the soil water content reached when the given crop with a fully developed root system is allowed to grow without irrigation until growth ceases. If the amount of water applied is known, then a function for W_d can also be used in equation (9).

Current Meteorological Data: Current meteorological data required for each region are: daily minimum and maximum air temperatures, daily solar radiation, daily dewpoint temperature, and total daily wind run for each day since the last computation date. An optional brief weather forecast can be included for each region, and a coefficient adjusting the expected E* for the next five days either upward or downward can be included based on current forecasts.

Current Field Data: Current data for each field are: date of the last irrigation, the allowable soil water depletion at the present stage of growth (this can be included in the program), and the rainfall and/or irrigation amount and its date of occurrence if it falls within the present computation period.

E. Output Data

The output data can be modified by the service groups to suit their operating procedures and facilities. A typical example of the output received by a farm manager is illustrated in Computer Output Sheet A.

A typical example of a portion of the output provided the farm managers receiving generalized forecasts of irrigation needs is given in Computer Output Sheet B.

F. Recent Modifications

Calibration of E* Equations: Under arid conditions, the constants in the Penman equation tend to underestimate E* during high advective conditions (Jensen et al., 1971; Rosenberg, 1969). Under these conditions, the magnitude of the aerodynamic portion of the combination equation is significantly larger than in semihumid areas. This can best be illustrated by use of several examples and a derivation similar to that presented by van Bavel (1966) as follows:

$$E^* = \frac{\Delta}{\Delta + \gamma} (R_n + G) + \frac{\gamma}{\Delta + \gamma} L B_v d_a \tag{11}$$

where L is the latent heat of vaporization; B_v is a transfer coefficient, g cm^{-2} min^{-1}; and d_a is the saturation vapor pressure deficit of the air, mb. By algebraic manipulation of equation (11) and the energy balance equation given in the next paragraph, it can be shown that:

$$L B_v d_a = E^* + \frac{\Delta}{\gamma} A \tag{12}$$

For the examples, assume the following energy balance equation and meteorological conditions:

$$E^* = (R_n + G) + A$$
$$T = 26°C$$
$$P = 1000 \text{ mb}$$

Under these conditions,

$$\Delta/\gamma = 3, \frac{\Delta}{\Delta + \gamma} = 0.75, \text{ and } \frac{\gamma}{\Delta + \gamma} = 0.25$$

Computer Output Sheet A

REGION:BURLEY-TWIN FALLS

FARM:JOHN DOE EXAMPLE   DATE OF COMPUTATION:JULY 28, 1969

| | | SOIL MOISTURE DEPLETION | | | IRRIGATIONS:LAST,NEXT & AMOUNT | | | |
CROP-FLD	COEF	TO DATE	OPTIMUM	RATE	LAST :	RAIN=0 :	W RAIN :	CM
W WHEAT	0.10	3.5	15	0.1	JUL 10	NONE 0	NONE 0	0
BEANS	1.01	1.8	5	.7	JUL 26	AUG 3	AUG 3	9
PEAS	0.10	11.0	11	.1	JUL 07	AUG 3	AUG 3	17
POTATOES	0.90	3.0	5	.6	JUL 24	AUG 1	AUG 1	7
SUG BEETS	0.90	3.7	8	.6	JUL 23	AUG 4	AUG 4	12
CORN	0.93	2.5	8	.6	JUL 25	AUG 5	AUG 5	12
ALFALFA	0.67*	12.3	18	.4	JUL 11	AUG 9	AUG 9	27
PASTURE	0.87	0.0	8	.6	JUL 28	AUG 10	AUG 10	12

PROBABLY RAIN NEXT TWO WEEKS = 0.1 CM

FORECAST:PARTLY CLOUDY & WARM

*The low coefficient for alfalfa reflects the effects of a recent cutting.

Computer Output Sheet B

CONSUMPTIVE USE AND SCHEDULING INFORMATION*
JULY 14, 1970 - A&B IRRIGATION DIST -2- SILT LOAM SOIL

DATE OF NEXT IRRIG AT LEFT IF DATE OF LAST IRRIG IS SHOWN BELOW

NEXT IRRIG	SUGBTS	POTATOES	S. GRAIN	BEANS	PEAS	CORN
JUL 14	JUN 28	JUL 5	JUN 26	JUL 5	JUL 3	JUN 30
JUL 15	JUN 29	JUL 7	JUN 27	JUL 6	JUL 4	JUL 1
JUL 16	JUL 1	JUL 8	JUN 29	JUL 7	JUL 5	JUL 2
JUL 17	JUL 2	JUL 10	JUN 30	JUL 9	JUL 6	JUL 4
JUL 18	JUL 2	JUL 11	JUN 30	JUL 10	JUL 7	JUL 5
JUL 19	JUL 3	JUL 12	JUL 1	JUL 11	JUL 8	JUL 6
JUL 20	JUL 4	JUL 12	JUL 2	JUL 12	JUL 9	JUL 7

*Computer Output Sheet 1970 - "General" Method. (Adapted from Figure 3, Brown and Buchheim [1971]).

Example (1) advective conditions:

$$(R_n + G) = 370 \text{ cal cm}^{-2} \text{ day}^{-1}$$
$$A = 130 \text{ cal cm}^{-2} \text{ day}^{-1}$$
$$E* = 500 \text{ cal cm}^{-2} \text{ day}^{-1}$$

From equations (11) and (12), the following results are obtained:

$$E* = 0.75(370) + 0.25[3(130) + 500] = 277.5 + 0.25(890) =$$

$$500 \text{ cal cm}^{-2} \text{ day}^{-1}$$

Example (2) sensible heat transfer to the air:

$$(R_n + G) = 370 \text{ cal cm}^{-2} \text{ day}^{-1}$$
$$A = -70 \text{ cal cm}^{-2} \text{ day}^{-1}$$
$$E* = 300 \text{ cal cm}^{-2} \text{ day}^{-1}$$

When these data are substituted into equations (11) and (12), the following results are obtained:

$$E* = 0.75(370) + 0.25[3(-70) + 300] = 277.5 + 0.25(90) =$$

$$300 \text{ cal cm}^{-2} \text{ day}^{-1}$$

These two examples clearly illustrate that the aerodynamic term becomes significantly larger when there is warm air advection. Consequently, the aerodynamic term must be more accurate under arid conditions where warm air advection is common (a negative mean daily Bowen ratio) than in semihumid areas where sensible heat is generally transferred to the air from the crop surface (a positive mean daily Bowen ratio).

Since the Penman equation underestimates E*, Wright and Jensen (1971) developed the following empirical coefficients for a linear wind function in equation (1) using lysimeter data and local U.S. Weather Service meteorological observations:

$$f(u) = 0.75 + 0.0114u_2 \qquad (13)$$

where u_2 is the windspeed measured at a height of 2 m in km day^{-1}. This wind function gives essentially the same results at moderate windspeeds as does the van Bavel

aerodynamic term $(7.15u_z/[\ln(z/z_o)]^2$ in place of $15.36(1.0 + 0.0062u_2)$ in equation (1), providing that the roughness parameter, z_o, is no greater than 1 cm.

Probability of Rainfall: Heermann and Jensen (1970) modified the computer program to include expected rainfall in predicting the date of the next irrigation. They also modified the estimates of expected potential evapotranspiration when the irrigation date is more than five days in the future, as follows:

$$E[E_{tp}] = E_{tp}' \exp\left[-\left(\frac{t - t'}{\Delta t}\right)^2\right] \qquad (14)$$

where $E[E_{tp}]$ is the expected value of potential evapotranspiration at a given day t (in Julian days); t' is the Julian calendar day when the maximum mean potential evapotranspiration, E_{tp}', occurs (about July 15 to July 25 in the northern hemisphere); and Δt is the days before and the days after t' when $E[E_{tp}] = 0.37E_{tp}'$. Normally a different value of Δt is used for $t \le t'$ as compared to $t > t'$. The major advantage of this procedure is that expected potential evapotranspiration is represented by a simple 3-parameter equation using E_{tp}', t', and Δt. For example, in southern Idaho $E_{tp}' = 0.81$ cm, $t' = 206$, and $\Delta t = 150$ for $t \le t'$ and 93 for $t > t'$.

Two expected dates of the next irrigation are then calculated: one assuming no rain, and one assuming 50% probable rainfall. Daily depletion is first calculated until $D \ge D_o$ using equations (9) and (15).

$$(E_t)_i = (K_c E[E_{tp}])_i \qquad (15)$$

Then this date is extended by the expected rainfall during the intervening period. If the next irrigation is predicted within the next five days, then $E[E_{tp}]$ is increased or decreased by a current forecast coefficient.

Effective Field Capacity: A better estimate of "effective field capacity" can be obtained by estimating cumulative drainage expected between irrigations. Estimates of the cumulative drainage, W_D, between irrigations can be obtained using the following equations that are based on the empirical relationship of water content and time for a soil that is draining:

$$W = cW_o t^{-m} \qquad (16)$$

where W is the water content in cm; W_0 the water content when $t = 1$; m is a constant for a soil; and c is a dimensional constant, t^m (Ogata and Richards, 1957). Accordingly,

$$\frac{dW}{dt} = -mW \left(\frac{W}{cW_0} \right)^{\frac{1}{m}} \tag{17}$$

The cumulative drainage can be calculated in a manner similar to that proposed by Wilcox (1962):

$$W_D = \sum_{i=1}^{\infty} m[W_{i-1} - (E_t)_i] \left(\frac{W_{i-1} - (E_t)_i}{W_0} \right)^{\frac{1}{m}} \tag{18}$$

where W_D is drainage, cm; i is the number of the day after irrigation; and E_t is the evapotranspiration for the day in cm. The most representative time to sample a soil that has been covered to prevent evaporation after a thorough irrigation can be obtained by integrating equation (17) between the limits of W_0 and W_D.

$$t = \left(\frac{cW_0}{W_0 - W_D} \right)^{\frac{1}{m}} \tag{19}$$

Since dW/dt rapidly $\to$ 0 using equation (17), about 5 to 20 days of calculations are needed before dW/dt < 0.01 cm day^{-1}. Example calculations based on data from southern Idaho and unpublished data from D.E. Miller (USDA-ARS-SWC, Prosser, Washington) are summarized in Table 2. In these examples, E_t was assumed to be 0.8 cm day^{-1}. In detailed laboratory measurements, Miller and Aarstad (1971) found that sampling 3.5 days after irrigation slightly underestimated the available water for the 0- to 70-cm depth, and sampling at 5.5 days closely represented the available water in the 0- to 120-cm depth with $E_t = 0.81$ cm day^{-1}. Equation (16) can be used to estimate drainage because the hydraulic gradient near the lower part of the profile at higher soil water levels is similar with or without E_t occuring.

TABLE 2
Estimated Time to Sample a Soil to Determine the
"Effective Field Capacity."

	Portneuf silt loam		Ritzville loam	
	0-60 cm	0-105 cm	0-60 cm	0-105 cm
W_o, cm	21.4	38.8	19.8	41.5
m	0.043	0.043	0.106	0.111
Daily E_t, cm	.8	.8	.8	.8
W_D, cm	.49	1.61	2.11	7.30
$W_o - W_D$, cm	20.91	37.19	17.69	34.20
t, days	1.7	2.7	2.9	5.7

G. Modifications Underway

If the water table level is relatively close to the soil surface or close to the bottom of the root zone, an adjustment can be included in the crop coefficients to account for the movement of water upward from the saturated zone using concepts presented by Gardner (1958). For bare soil, the amount of water moving upward, W_u, can be estimated using:

$$W_u = 0.9 \left(\frac{z_c}{z_w}\right)^n E_{tp} \qquad (20)$$

$$\text{for } z_w \geq z_c$$

with a crop,

$$W_u = \left[1 - \frac{AM - a_4}{100 - a_4}\right]\left[\frac{z_c}{z_w - z_r}\right]^n E_t \qquad (21)$$

where z_c is the effective height of the capillary fringe above the water table, cm; z_w is the depth to the water table, cm; z_r is the depth of roots, cm; AM is available soil

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water to z_r in percent; a_4 is a constant (about 25); and n
is a constant for a given soil and crop (expected to vary
between 1 and 3). An example of this approximation of W_u
is presented in Figure 1 using unpublished data from L.N.
Namken (USDA-ARS-SWC, Weslaco, Texas). (Constants used in
equation (20) are z_w = 273 cm, z_c = 50 cm, n = 1.22, and
a_4 = 25%.)
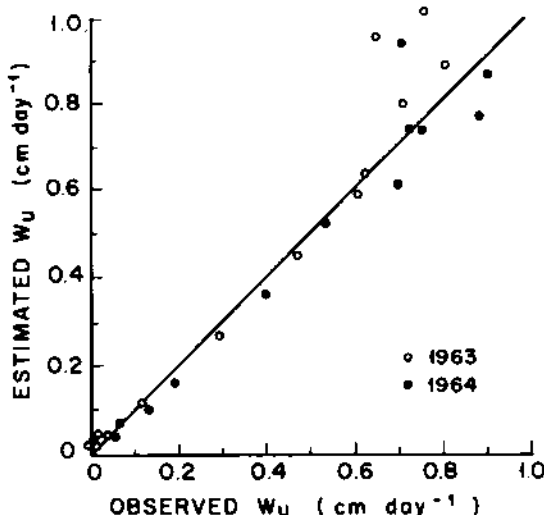

Figure 1. Comparison of estimated weekly mean amount
of water moving upward, W_u, with observed W_u. (Observed
data provided by L.N. Namken, USDA-ARS-SWC, Weslaco, Texas.)

accuracy of all projected irrigations.

Summary

Irrigation programming practices have not changed appreciably in many areas during the past three decades because suggested techniques have not been acceptable, and the direct and indirect effects of excessive water use were not readily apparent. Several alternative methods of programming irrigations are now available. The scheduling of irrigations for each field using meteorological, soil, and crop data, coupled with field inspection, appears to be an economical and acceptable irrigation management service in the U.S.A. An irrigation management service requires technical competence and a good communications network. Reliable meteorological data also require technical competence, and periodic calibration of instruments.

The USDA-ARS-SWC irrigation scheduling computer program using meteorological techniques and soil-crop data is described in this chapter. Since its development and use for several years in Arizona, Idaho, and Nebraska, several modifications have been completed and others are under way. This problem has enabled private firms and service agencies to gain experience in providing irrigation management service while additional refinements are under way.

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